Cosmoparticle Physics - the Challenge to the Millenium

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Abstract

Cosmoparticle physics offers the exciting challenge for the new Millenium to come to the true knowledge on the basic natural laws and on the way, they govern the creation and evolution of the Universe with all the forms of its present energy content. The theory of everything, the true history of the Universe, based on it, the new sources of energy release and the new means of energy transfer should come from the prospects of cosmoparticle physics. We may be near the first positive results in this direction. The methods of cosmoparticle physics are briefly reviewed.

1 Introduction

The modern cosmology implies A) inflation, B) baryosynthesis and C) dark matter and energy, what inevitably leads to the whole ABC, with which the NATURE writes the true WORDS in the BOOK (BIBLIO) on the History and Fate of the Universe. Cosmoparticle physics is aimed to find these Words, and to face on without fear the WORD, which was put into the Beginning of Creation. Treating the Universe as the physical process, the methods, developed by cosmoparticle physics, resolve the main problem of the modern cosmology: they probe the true picture of the cosmological evolution together with the whole set of physical laws, governing it. Based on the fundamental relationship between micro- and macro worlds, cosmoparticle physics offers the cross-disciplinary studies of the foundations of particle physics and cosmology in the proper combination of their indirect cosmological, astrophysical and physical signatures.

Cosmoparticle physics originates from the well established relationship between microscopic and macroscopic descriptions in theoretical physics. Remind the links between statistical physics and thermodynamics, or between electrodynamics and theory of electron. Turning to the role of microscopic properties in macroscopic phenomena or to the investigation of microscopic processes by their macroscopic effects, we, in fact, indirectly use the ideas of cosmoparticle physics. In this sense all the methods of experimental study of elementary particles are based on these ideas, as well as these ideas underlie

the theoretical description of astrophysical processes. To the end of the XX Century the new aspects of such links were realised in cosmological necessity for the extension of the world of known elementary particles and their interactions and in the necessity for particle theory to use cosmological tests as the unique way to probe its predictions.

Being the last word of the fundamental physics of XX Century, cosmoparticle physics offers to the new millennium the set of questions. Their proper formulation is more than half of their proper answers. There are serious grounds to expect in the very near future definite answers on some of these questions. It specifies the modern step of development of cosmoparticle physics: on the basis of its principles and in its framework it not only sheds new light and offers nontrivial solutions for old astronomical problems but also comes to positive predictions of new phenomena, accessible for their search.

2 The "ecological" aspects of the modern cosmology

Ecology studies the mutual relationship between the population and its environment. In this sense the mutual relationship between the fundamental particle content, particle interactions and the structure and evolution of the Universe, studied by cosmoparticle physics, is ecological.

Lets specify the links between fundamental particle properties and their cosmological effects in some more details. The role of particle content in the Einstein equations is reduced to its contribution into energy-momentum tensor. So, the set of relativistic species, dominating in the Universe, realises the relativistic equation of state $p = \epsilon/3$ and the relativistic stage of expansion. The difference between relativistic bosons and fermions or various bosonic (or fermionic) species is accounted by the statistic weight of respective degree of freedom. The very treatment of different species of particles as equivalent degrees of freedom physically assumes strict symmetry between them.

Such strict symmetry is not realised in Nature. There is no exact supersymmetry (symmetry between bosons and fermions). There is no exact symmetry between various quarks and leptons. The symmetry breaking results in generation of particle masses. The particle mass pattern reflects the hierarchy of symmetry breaking.

Noether's theorem relates the exact symmetry to conservation of respective charge. The lightest particle, bearing the strictly conserved charge, is absolutely stable. So, electron is absolutely stable because of the conserva-

tion of electric charge. The mass of electron m_e is related to the scale of the electroweak symmetry breaking, Λ_{EW}: the standard model gives the electron mass as $m_e = g_e \Lambda_{EW}$, where g_e is the Higgs field Yukawa coupling. In the same manner the stability of proton is conditioned by the conservation of baryon charge and its mass reflects the chiral symmetry breaking being determined by the scale of QCD confinement, Λ_{QCD}. The stability of ordinary matter is thus protected by the conservation of electric and baryon charges, and its properties reflect the fundamental physical scales of electroweak and strong interactions.

Extensions of the standard model imply new symmetries and new particle states. The respective symmetry breaking induces new fundamental physical scales in particle theory. If the symmetry is strict, its existence implies new conserved charge. The lightest particle, bearing this charge, is stable. The set of new fundamental particles, corresponding to the new symmetry, is then reflected in the existence of new stable particles, which should be present in the Universe and taken into account in the total energy-momentum tensor.

Most of the known particles are unstable. For a particle with the mass m the particle physics time scale is $t \sim \frac{1}{m}$, so in particle world we refer to particles with lifetime $\tau \gg \frac{1}{m}$ as to metastable. To be of cosmological significance metastable particle should survive after the temperature of the Universe T fell down below $T \sim m$, what means that the particle lifetime should exceed $t \sim \frac{m_{Pl}}{m} \cdot \frac{1}{m}$. Such a long lifetime should find reason in the existence of an (approximate) symmetry. From this viewpoint, cosmology is sensitive to the most fundamental properties of microworld, to the conservation laws reflecting strict or nearly strict symmetries of particle theory.

However, the mechanism of particle symmetry breaking can also have the cosmological impact. Heating of condensed matter leads to restoration of its symmetry and to formation of topological defects in the course of phase transitions, corresponding to symmetry breaking. One can directly observe formation of such defects in liquid crystals or in superfluids. In the same manner the mechanism of spontaneous symmetry breaking should reflect in restoration of symmetry and, depending on the symmetry breaking pattern, to formation of topological defects in phase transitions in very early Universe. The defects can represent the new form of stable particles (as it is in the case of magnetic monopoles), or the form of extended structures, such as cosmic strings or cosmic walls. In the latter case primordial strong non-homogeneity appears, triggering gravitational instability.

In the old Big bang scenario the cosmological expansion and its initial conditions was given *a priori*. The whole set of fundamental particles, most of which are unstable, was taken into account in the conditions of thermodynamic equilibrium, and the number of particle species entered the rela-

tionship between the temperature and cosmological time. The properties of stable particles cause much more influence on the physics of expansion. The baryon mass at initially given baryon to photon ratio determines the change of equation of state in the transition from radiation to matter dominance. The chemical composition, resulting from primordial nucleosynthesis is defined by the rate of beta-reactions, determining the neutron to proton frozen out ratio, by nuclear reaction rates and Coulomb interaction (defining the Coulomb barrier in reactions with electrically charged nuclei). The period of recombination of hydrogen is determined by electron mass and its Coulomb interaction and scales of gravitational instability is defined by the dissipation scale, being in turn determined by photon-electron Compton scattering. In the framework of standard model of particle interactions the above microphysical parameters reflect the QCD and electroweak scales. In the early Universe, when the temperature was of the order of these scales the QCD and electroweak phase transitions should have taken place.

In the modern cosmology the expansion of the Universe and its initial conditions is related to the process of inflation. The global properties of the Universe as well as the origin of its large scale structure are the result of this process. The matter content of the modern Universe is also originated from the physical processes: the baryon density is the result of baryosynthesis and the nonbaryonic dark matter represents the relic species of physics of the hidden sector of particle theory. Physics, underlying inflation, baryosynthesis and dark matter, is referred to the extensions of the standard model, and the variety of such extensions make the whole picture in general ambiguous. However, in the framework of each particular physical realisation of inflationary model with baryosynthesis and dark matter the corresponding model dependent cosmological scenario can be specified in all the details. In such scenario the main stages of cosmological evolution, the structure and the physical content of the Universe reflect the structure of the underlying physical model. The latter should include with necessity the standard model, describing the properties of baryonic matter, and its extensions, responsible for inflation, baryosynthesis and dark matter. In no case the cosmological impact of such extensions is reduced to reproduction of these three phenomena only. The nontrivial path of cosmological evolution, specific for each particular realisation of inflational model with baryosynthesis and nonbaryonic dark matter, always contains some additional model dependent cosmologically viable predictions, which can be confronted with astrophysical data. The part of cosmoparticle physics, called cosmoarcheology, offers the set of methods and tools probing such predictions.

3 Cosmoarcheology of new physics in the modern cosmology

Cosmoarcheology considers the results of observational cosmology as the sample of the experimental data on the possible existence and features of hypothetical phenomena predicted by particle theory. To undertake the *Gedanken Experiment* with these phenomena some theoretical framework for treatment of their origin and evolution in the Universe should be assumed. As it was pointed out [1] the choice of such framework is a nontrivial problem in the modern cosmology.

Indeed, in the old Big bang scenario any new phenomenon, predicted by particle theory was considered in the course of the thermal history of the Universe, starting from Planck times. The problem is that the bedrock of the modern cosmology, namely, inflation, baryosynthesis and dark matter, is also based on experimentally unproven part of particle theory, so that the test for possible effects of new physics is accomplished by the necessity to choose the physical basis for such test. There are two possible solutions for this problem: a) a crude model independent comparison of the predicted effect with the observational data and b) the model dependent treatment of considered effect, provided that the model, predicting it, contains physical mechanism of inflation, baryosynthesis and dark matter.

The basis for the approach (a) is that whatever happened in the early Universe its results should not contradict the observed properties of the modern Universe. The set of observational data and, especially, the light element abundance and thermal spectrum of microwave background radiation put severe constraint on the deviation from thermal evolution after 1 s of expansion, what strengthens the model independent conjectures of approach (a).

One can specify the new phenomena by their net contribution into the cosmological density and by forms of their possible influence on parameters of matter and radiation. In the first aspect we can consider strong and weak phenomena. Strong phenomena can put dominant contribution into the density of the Universe, thus defining the dynamics of expansion in that period, whereas the contribution of weak phenomena into the total density is always subdominant. The phenomena are time dependent, being characterised by their time-scale, so that permanent (stable) and temporary (unstable) phenomena can take place. They can have homogeneous and inhomogeneous distribution in space. The amplitude of density fluctuations $\delta \equiv \frac{\delta\rho}{\rho}$ measures the level of inhomogeneity. The case $\delta \geq 1$ within the considered component corresponds to its strong inhomogeneity. Strong inhomogeneity is compat-

ible with the smallness of total density fluctuations, if the contribution of inhomogeneous component into the total density is small.

The phenomena can influence the properties of matter and radiation either indirectly, say, changing of the cosmological equation of state, or via direct interaction with matter and radiation. In the first case only strong phenomena are relevant, in the second case even weak phenomena are accessible to observational data. The detailed analysis of sensitivity of cosmological data to various phenomena of new physics are presented in [2].

The basis for the approach (b) is provided by a particle model, in which inflation, baryosynthesis and nonbaryonic dark matter is reproduced. Any realisation of such physically complete basis for models of the modern cosmology contains with necessity additional model dependent predictions, accessible to cosmoarcheological means. Here the scenario should contain all the details, specific to the considered model, and the confrontation with the observational data should be undertaken in its framework. In this approach complete cosmoparticle physics models may be realised, where all the parameters of particle model can be fixed from the set of astrophysical, cosmological and physical constraints. Even the details, related to cosmologically irrelevant predictions, such as the parameters of unstable particles, can find the cosmologically important meaning in these models. So, in the model of horizontal unification, the top quark or B-meson physics fixes the parameters, describing the dark matter, forming the large scale structure of the Universe.

4 Cosmophenomenology of new physics

To study the imprints of new physics in astrophysical data cosmoarcheology implies the forms and means in which new physics leaves such imprints. So, the important tool of cosmoarcheology in linking the cosmological predictions of particle theory to observational data is the *Cosmophenomenology* of new physics. It studies the possible hypothetical forms of new physics, which may appear as cosmological consequences of particle theory, and their properties, which can result in observable effects.

The simplest primordial form of new physics is the gas of new stable massive particles, originated from early Universe. For particles with the mass m, at high temperature $T > m$ the equilibrium condition, $n \cdot \sigma v \cdot t > 1$ is valid, if their annihilation cross section $\sigma > \frac{1}{m m_{Pl}}$ is sufficiently large to establish the equilibrium. At $T < m$ such particles go out of equilibrium and their relative concentration freezes out. More weakly interacting species decouple from plasma and radiation at $T > m$, when $n \cdot \sigma v \cdot t \sim 1$, i.e. at $T_{dec} \sim (\sigma m_{Pl})^{-1}$. The maximal temperature, which is reached in inflationary Universe, is the

reheating temperature, T_r, after inflation. So, the very weakly interacting particles with the annihilation cross section $\sigma < \frac{1}{T_r m_{Pl}}$, as well as very heavy particles with the mass $m \gg T_r$ can not be in thermal equilibrium, and the detailed mechanism of their production should be considered to calculate their primordial abundance.

Decaying particles with the lifetime τ, exceeding the age of the Universe, t_U, $\tau > t_U$, can be treated as stable. By definition, primordial stable particles survive to the present time and should be present in the modern Universe. The net effect of their existence is given by their contribution into the total cosmological density. They can dominate in the total density being the dominant form of cosmological dark matter, or they can represent its subdominant fraction. In the latter case more detailed analysis of their distribution in space, of their condensation in galaxies, of their capture by stars, Sun and Earth, as well as of the effects of their interaction with matter and of their annihilation provides more sensitive probes for their existence. In particular, direct experimental search for cosmic fluxes of weakly interacting massive particles (WIMPs) is possible. WIMP annihilation in galactic halo contributes into the fluxes of cosmic rays, and their annihilation in Sun and Earth is the source of neutrinos accessible to underground neutrino observatories. New particles with electric charge and/or strong interaction can form anomalous atoms and contain in the ordinary matter as anomalous isotopes.

Primordial unstable particles with the lifetime, less than the age of the Universe, $\tau < t_U$, can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition $\tau \gg \frac{m_{Pl}}{m} \cdot \frac{1}{m}$, their existence in early Universe can lead to direct or indirect traces. Cosmological flux of decay products contributing into the cosmic and gamma ray backgrounds represents the direct trace of unstable particles. If the decay products do not survive to the present time their interaction with matter and radiation can cause indirect trace in the light element abundance or in the fluctuations of thermal radiation. If the particle lifetime is much less than 1s the multi-step indirect traces are possible, provided that particles dominate in the Universe before their decay. On the dust-like stage of their dominance black hole formation takes place, and the spectrum of such primordial black holes traces the particle properties (ma! ! ss, frozen concentration, lifetime). The particle decay in the end of dust like stage influences the baryon asymmetry of the Universe. So cosmophenomenoLOGICAL chains link the predicted properties of even unstable new particles to the effects accessible in astronomical observations.

The parameters of new stable and metastable particles are determined by the pattern of particle symmetry breaking. This pattern is reflected in the succession of phase transitions in the early Universe. The phase tran-

sitions of the first order proceed through the bubble nucleation, which can result in black hole formation. The phase transitions of the second order can lead to formation of topological defects, such as walls, string or monopoles. The observational data put severe constraints on magnetic monopole and cosmic wall production, as well as on the parameters of cosmic strings. The succession of phase transitions can change the structure of cosmological defects. The more complicated forms, such as walls-surrounded-by-strings can appear. Such structures can be unstable, but their existence can lead the trace in the nonhomogeneous distribution of dark matter and in large scale correlations in the nonhomogeneous dark matter structures, such as *archioles*. The large sc! ! ale correlations in topological defects and their imprints in primordial inhomogeneities is the indirect effect of inflation. Inflation provides the equal conditions of phase transition, taking place in causally disconnected regions. Phase transitions, taking place directly at inflational stage, can lead to strong inhomogeneity at any scale, Which can lead to formation of primordial black holes of a whatever large mass. In the combination with successive phase transitions, taking place after reheating, phase transitions at inflational stage can result in such structures as closed walls of any size, collapsing into black holes after their size equals the horizon. So the primordial strong inhomogeneities is the new important phenomenon of cosmological models, based on particle models with hierarchy of symmetry breaking.

5 Experimental probes for new physics

The new physics follows from the necessity to extend the Standard model. The white spots in the representations of symmetry groups, considered in the extensions of the Standard model, correspond to new unknown particles. The extension of the symmetry of gauge group puts into consideration new gauge fields, mediating new interactions. Global symmetry breaking results in the existence of Goldstone boson fields.

For a long time the necessity to extend the Standard model had purely theoretical reasons. Esthetically, because full unification is not achieved in the Standard model; practically, because it contains some internal inconsistencies. It does not seem complete for cosmology. One has to go beyond the Standard model to explain inflation, baryosynthesis and nonbaryonic dark matter. Recently there has appeared a set of experimental evidences for the existence of neutrino oscillations and WIMPs, and for the effects of new particles in the precise measurements of muon magnetic momentum. Whatever convincing and reliable these evidences are, they indicate that may be

we have already crossed the border in the experimental searches for new physics.

In particle physics direct experimental probes for the predictions of particle theory are the most attractive. The predictions of new charged particles, such as supersymmetric particles or quarks and leptons of new generation, are accessible to experimental search at accelerators of new generation, if their masses are in 100GeV-1TeV range. However, the predictions related to higher energy scale need non-accelerator or indirect means for their test.

The search for rare processes, such as proton decay, neutrino oscillations, neutrinoless beta decay, precise measurements of parameters of known particles, experimental searches for dark matter represent the widely known forms of such means.

Cosmoparticle physics offers the nontrivial extensions of indirect and non-accelerator searches for new physics and its possible properties. In experimental cosmoarcheology the data is to be obtained, necessary to link the cosmophenomenology of new physics with astrophysical observations (See [1]). In experimental cosmoparticle physics the parameters, fixed from the consitency of cosmological models and observations, define the level, at which the new types of particle processes should be searched for (see [3]).

Note that there is a way, in which new physics may be elusive for the existing methods of experimental particle physics: the higher is the energy of colliding particles the higher is the resolution in small spatial scales, but if some abnormal forms of particles exist, being extended in space, their existence can escape detection. For example, if some fictious spatially isomeric form of proton existed, having the form of a rod with the molecular size length, it could hardly been detected by the means of deep inelastic collisions. For the moment, there is no theoretical reasoning for such exotic forms of known particles, but the principal possibility for such solutions can not be ignored.

6 Cosmoparticle physics of theories of everything

The theories of everything should provide the complete physical basis for cosmology. The problem is that the string theory [4] is now in the form of "theoretical theory", for which the experimental probes are widely doubted to exist. The development of cosmoparticle physics can remove these doubts. In its framework there are two directions to approach the test of theories of everything.

One of them is related with the search for the experimentally accessible effects of heterotic string phenomenology. The mechanism of compactification and symmetry breaking leads to the prediction of homotopically stable objects [5] and shadow matter [6], accessible to cosmoarcheological means of cosmoparticle physics. The condition to reproduce the Standard model naturally leads in the heterotic string phenomenology to the prediction of fourth generation of quarks and leptons [7] with a stable massive 4th neutrino [8], what can be the subject of complete experimental test in the near future. Moreover, there are evidences from EGRET galactic gamma-background measurements and underground WIMP searches, favoring the hypothesis of 4th neutrino with the mass about 50 GeV, and it was recently shown that capture and annihilation of such neutrinos and their antineutrinos inside the Earth, should lead to the flux of underground monochromatic neutrinos of known types, which can be traced in the analysis of the already existing data of underground neutrino detectors [9].

It is interesting, that heterotic string phenomenology predicts even in its simplest realisation both supersymmetric particles and the 4th family of quarks and leptons. Provided that both R-parity and the new gauge charge, ascribed to the 4th generation, are strictly conserved, the same model predicts simultaneously two types of WIMP candidates: neutralinos and massive stable 4th neutrinos. So in the framework of this phenomenology the multicomponent analysis of WIMP effects is favorable.

In the above approach some particular phenomenological features of simplest variants of string theory are studied. The other direction is to elaborate the extensive phenomenology of theories of everything by adding to the symmetry of the Standard model the (broken) symmetries, which have serious reasons to exist. The existence of (broken) symmetry between quark-lepton families, the necessity in the solution of strong CP-violation problem with the use of broken Peccei-Quinn symmetry, as well as the practical necessity in supersymmetry to eliminate the quadratic divergence of Higgs boson mass in electroweak theory is the example of appealing additions to the symmetry of the Standard model. The horizontal unification and its cosmology represent the first step on this way, illustrating the might of cosmoparticle physics in the elaboration of the proper phenomenology for theories of everything [10].

7 Conclusion

We can conclude that our ideas on the Universe experience the dramatic change, comparable with the one, caused by the Copernicus idea that Earth moves around Sun and by the Friedman's idea on the non-stationary Uni-

verse. From the very beginning to the modern stage, the evolution of Universe is governed by the forms of matter, different from those we are built of and observe around us. From the very beginning to the present time, the evolution of the Universe was governed by physical laws, which we still don't know. Observational cosmology offers strong evidences favouring the existence of processes, determined by new physics. Obsevations favor the dominance of new forms of matter in the total energy of the modern Universe.

Cosmoparticle physics, studying the physical, astrophysical and cosmological impact of new laws of Nature, explores the new forms of matter and their physical properties, what opens the way to use the corresponding new sources of energy and new means of energy transfer. It offers the great challenge for the new Millennium.

It's regrettful, that A.D.Sakharov isn't now with us on this way, but he was with us in its beginning [11], and it's the aim of the present conference to present the new step in the development of Sakharov's legacy in the field of cosmoparticle physics [12].

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